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EVALUATION OF BLUETOOTH LOW ENERGY TECHNOLOGY FOR TEAM SPORTS REAL-TIME PHYSIOLOGICAL MONITORING

Master's thesis

Examiner: Assistant Prof. Antti Vehkaoja

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Tämän diplomityön aiheena oli evaluoida langattoman Bluetooth Low Energy (BLE) -teknologian käyttämistä joukkueurheilijoiden reaaliaikaiseen monitorointiin. Valmentajat pystyvät hyödyntämään reaaliaikaista monitorointia harjoituksien aikana, minkä avulla harjoituskuormaa pystytään seuraamaan. Tässä työssä mitattu datan laatu ja järjestelmän luotettavuus olivat korkeasti priorisoituja teknologian soveltuvuutta arvioitaessa. Laitteilla mitattu fysiologinen data on sydämen sykettä ja sykevälivaihtelua. Sykevälivaihtelun avulla voidaan analysoida urheilijoiden rasitus- ja lepotiloja. Huippu-urheilussa pienetkin erot ovat ratkaisevia ja sen vuoksi joukkueet ovat kiinnostuneita urheilijoiden optimaalisesta harjoittelusta.

Työssä BLE-mainospakettien seurannan avulla pystyttiin evaluoimaan teknologian toimintaa eri olosuhteissa, sillä mainospakettien avulla saadaan signaalin voimakkuus ja mainospakettihävikki selville. Tarkoituksena oli löytää parhaat asetukset maksimaalisen etäisyyden ja mahdollisimman pienen BLE-mainospakettihävikin kannalta. Reaaliaikaisen monitorointijärjestelmän täytyy pystyä vastaanottamaan dataa 30 laitteelta samanaikaisesti.

Sydämen syke lähetettiin BLE-mainospakettien mukana reaaliaikaisen monitoroinnin aikana. BLE:n toimivuutta testattiin eri olosuhteissa, jotta tiedämme kyseisen langattoman teknologian suorituskyvyn ja siihen liittyvät rajoitteet. Langattomassa tiedonsiirrossa häviää BLE-mainospaketteja ja tämän vuoksi tallensimme mittauksen aikana saadut sykevälit mittalaitteen sisäiseen muistiin. Lisäksi datan tallentaminen ja lataaminen laitteen muistista olivat työssä evaluoitavia asioita.

Reaaliaikaisen monitorointijärjestelmän testausta tehtiin vaativissa olosuhteissa myös oikeille testihenkilöille. Testiprotokollat suunniteltiin järjestelmän vaatimuksien mukaan. Tämän työn tuloksien perusteella BLE-teknologia vaikuttaa sopivalta joukkueurheilijoiden reaaliaikaiseen monitorointiin ja tulevaisuudessa voidaan keskittyä järjestelmän validointiin.

ABSTRACT

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The goal of this thesis was to evaluate and test a new sensor system for real-time monitoring of professional athletes. Real-time monitoring of physiological data can be used by the coaches to analyze and improve the training of individual athletes or teams. In this work data quality and reliability of the sensor system were highly prioritized. Physiological data measured is based on the heart rate (HR) and heart rate variability (HRV). HRV gives valuable information on the training intensity and recovery of athletes. In competitive sport insightful information on the physical conditions of the athletes gives team cutting edge for success. Real-time monitoring system needs to be easy to use and set up to be in daily use for sports teams.

The objective for evaluation was to research how the distance between sensors, number of devices, different environments and settings affect to the Bluetooth Low Energy (BLE) advertising packet loss. The purpose was to find optimal settings for maximal range and minimal advertising packet loss ratio while being able to handle real-time monitoring of up to 30 devices simultaneously.

Sensors tested and evaluated for this work are using BLE technology, which enables good compatibility with various end devices on the market. For real-time monitoring of multiple sensors, BLE advertising mode was used. Different methods were used to test the functionality of the BLE advertising mode. A high emphasis was put on the range and packet loss. To ensure that all the data is safely secured the sensor is programmed to save all the measurements during training sessions to the internal memory of the sensor. Reading data from memory was also part of the testing and evaluation of the sensor.

Tests were done using between 1-30 sensors simultaneously for real-time monitoring. In most of the user cases, the ability to monitor up to 30 athletes is sufficient. Test protocols were selected according to the needs and aim of the sensor evaluation. All the test subjects were volunteers and gave their consent to use their physiological data to this project. According to the evaluation results, there is a possibility to start the commercialization of this sensor platform. The further tests are needed for verification and a Proof of concept (PoC).

PREFACE

Writing of this Master's thesis started while working at the faculty of the Biomedical Sciences and Engineering at the Tampere University of Technology and work continued at the Firstbeat Technologies Ltd.

I would like to give special thanks to my examiner Assistant Professor Antti Vehkaoja for his support during writing this thesis, and my supervisor Adjunct Professor Ilkka Korhonen for an opportunity to do this thesis. Also, I would like to thank my co-workers from Firstbeat Technologies who are working on this project.

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ABBREVIATIONS AND NOTATIONS

AFH	Adaptive Frequency Hopping
ANS	Autonomic nervous system
API	Application programming interface
ATT	Attribute Protocol
BLE	Bluetooth Low Energy
BT	Bluetooth
CPU	Central processing unit
D2D	Device-to-device
EEPROM	Electrically erasable read-only memory
ECDH	Elliptic Curve Diffie Hellman public key cryptography
ECG	Electrocardiogram
EPOC	Excess post-exercise oxygen consumption
GATT	Generic Attribute Profile
GAP	Generic Access Protocol
GLONASS	Global Navigation Satellite System
GPS	Global Positioning System
HR	Heart rate
HRV	Heart rate variability
HTTP	Hypertext Transfer Protocol
ISM	Unlicensed industrial, scientific and medical frequency band
LED	Light-emitting diode
MCU	Microcontroller unit
M2M	Machine-to-machine
OR	Overreaching
OS	Operating system
OT	Overtraining
PDU	Protocol data unit
PoC	Proof of concept
REST	Representational State Transfer
RRI	R-R interval, the time interval between heartbeats
SD	Standard deviation
SIG	Special interest group
SoC	System on a chip
TE	Training effect
TL	Training load
VO_2	Oxygen consumption
WLAN	Wireless local area network

1. INTRODUCTION

Wearables and health monitoring have been big trends in recent years. Therefore, demand for more accurate and effective monitoring systems is increasing. Professional sports teams are continuously looking for ways to get ahead of their competitors, and thus monitoring of training is needed to keep the athletes in optimal condition [1]. Real-time physiological monitoring enables better communication between coaches and athletes when the coach can see training loads (TL) in real-time and give feedback to athletes. New methods and parameters to analyze physiological data are needed to provide valuable information to coaches [2].

Athletes can easily train too heavily. This can lead to overtraining (OT), which can be prevented by monitoring the physiological status of the athlete. OT is a common problem with athletes and can be hard to detect without access to physiological data [3].

Along with heart rate (HR), heart rate variability (HRV) is essential for monitoring recovery and TL of the athletes [4]. HRV is defined as time variation between heartbeats and it is related to the activity of the autonomic nervous system (ANS) [4, 5]. A healthy heart has some level of HRV and reduced HRV can be a predictor of future health problems. OT and diseases can change the activity of the ANS, which affects HRV [6, 7]. Electrocardiography (ECG) is generated by electrical potential changes in the heart during a cardiac cycle. To detect HRV sensor is needed to measure the ECG signal from the skin of the subject. HRV is calculated from R-R intervals (RRI) that are visible in the ECG signal [5].

The main objective of this Master's thesis is to evaluate and test a new sensor platform for real-time monitoring of athletes. This real-time monitoring system consists of heart rate sensor with chest strap and mobile device for receiving physiological data. Multiple sensors and features are integrated into the heart rate sensor along with programmability. The connection between sensors and the mobile device is based on Bluetooth Low Energy (BLE) protocol. BLE is a great protocol for machine-to-machine (M2M) communication because of the various compatible devices on the market. The advertising mode in BLE is tested for real-time monitoring of HR and simultaneously storing of RRI data to the internal memory of the device. It is important to find out the limits and capability of this system.

Firstly, in this thesis we will get comprehensive knowledge of BLE protocol and different data transmission modes and specifications. After background information, we will present more about the materials and methods used for implementing tests. The following chapter is for measurements and results, which includes test results and statistical analysis of the data.

The final chapter of the thesis discusses how well this system worked and presents conclusions and what are the next steps for the development. Suitability of the BLE protocol for real-time monitoring of athletes will be concluded in this chapter.

2. BACKGROUND

There are multiple wireless communication technologies that are suitable for physiological real-time monitoring of athletes. However, professional sports are demanding and there are high expectations for performance and reliability. The first critical aspect of this project is that the real-time monitoring system has the ability to secure all recorded data. Therefore, internal memory for physiological data recording is needed. Secondly, the system should be easy to use and reliable.

Advantages and disadvantages of the communication technologies should be viewed carefully. For this real-time monitoring system, Bluetooth Low Energy (BLE) standard seems to be convenient. BLE is already used in various product categories, such as medical devices and consumer electronics. BLE enables a secure device-to-device (D2D) connection using Elliptic Curve Diffie Hellman (ECDH) public key cryptography, which is useful for transferring physiological data from internal memory of the sensor to a mobile device. ECDH cryptography was introduced in BLE 4.2 version and had stronger security compared to earlier versions of BLE. [8, 9]

Another goal of this thesis is to evaluate how well storing of RRI data to internal memory is working. The sensor device has internal electrically erasable read-only memory (EEPROM) that can be utilized for storing measurement data.

Firstly, in this chapter we go through physiological real-time monitoring systems on the market and benefits of the physiological monitoring. After that, we present the comparison between different wireless communication technologies and we explain why BLE was chosen for this real-time monitoring system. Then we discuss more about Bluetooth and BLE specifications and different data transmission modes. At the end of the chapter, we will briefly present EEPROM in comparison with different memory types.

2.1 Physiological real-time monitoring systems

There are several companies offering physiological monitoring solutions on the market. However, there are not many companies offering real-time monitoring systems for team sports. In this chapter, we present companies and services related to physiological real-time monitoring systems.

Firstbeat Technologies Ltd is a physiological analytics company focused on sports and well-being. The company was founded in 2002 in Jyväskylä, Finland. Firstbeat Technologies has a real-time monitoring system called Firstbeat Sports. Firstbeat Sports uses BlueRobin communication technology for data transmission with the range up to 200 meters and it uses chest straps for measuring HR and HRV data. Today, over 800 professional sports teams and over 50 percent of all the NHL ice hockey teams are using Firstbeat Sports. This real-time monitoring system gives insight about training loads (TE) and other parameters for monitoring the overall fitness of the athletes. Firstbeat Sports Team monitoring system is presented in Figure 1. [10, 11]

Figure 1. Firstbeat Sports Team Pack includes HR chest straps, data receiver, laptop, sport bag and Bodyguard 2 for recovery monitoring. [12]

Another real-time monitoring system is made by a Finnish company called Polar Electro. Polar Electro was founded in 1977 and they have developed and launched the world's first wireless heart rate monitor. Polar Electro has a wide range of consumer products including sports watches and heart rate monitors. Their real-time team sports monitoring system is called Team Pro. Team Pro uses Bluetooth for real-time data collection and has a range up to 200 meters. Team Pro measures HR along with the GPS (Global Positioning System) and motion data. GPS can track where players are located on the field and how long distance they have moved. Motion data is measured using an accelerometer, gyroscope, and magnetometer. Operating time for each sensor is 10 hours and they can be recharged in 3 hours using the Team Pro charging dock. Team Pro can monitor up to 60 players in real-time and enables live comparison between players. Polar Team Pro is shown in Figure 2. [13, 14]

Figure 2. Polar Team Pro monitoring system includes charging dock for the HR sensors and iPad for real-time data acquisition. [15]

Catapult Sports is an Australian based company offering solutions for sports monitoring. Catapult Sports was founded in 2006 by Shaun Holthouse and Igor van de Griendt. Their real-time monitoring systems are used by over 1500 sports teams around the world. Catapult Sports flagship product is called ClearSky T6, which uses license-free ultra-wideband communication technology enabling real-time monitoring of up to 120 players simultaneously. ClearSky T6 is also equipped with Bluetooth connectivity for external applications. The device can measure HR and 9-D (nine-dimensional) motion data using accelerometer, gyroscope, and magnetometer. The company has also another product called OptimEye S5 which offers HR and accurate GPS and GLONASS (Global Navigation Satellite System) location data. Catapults Sports ClearSky T6, OptimEye S5 and OptimeEye X4 are displayed in Figure 3. [16, 17]

Figure 3. Catapult Sports ClearSky T6, OptimEye S5, OptimEye X4 and software for analyzing data during a real-time monitoring. [18]

2.2 Benefits of the physiological monitoring

Monitoring of the heart rate (HR) and heart rate variability (HRV) during exercise provides data that can be used to improve training. Benefits of the real-time monitoring are high especially during interval training and other intensive exercises. Effective training can improve cardiorespiratory fitness. To achieve the desired training effect (TE), variations between exercises are needed. Exercise intensity can be monitored by the percentage of the maximal heart rate, e.g. at high-intensity training typical heart rate is above 85% of the maximal heart rate. [19]

Understanding training loads (TL) and the recovery are important for the athletes to improve their athletic performance. TL stands for the status of the total load and the stress body has gained during the exercises. The autonomic nervous system (ANS) controls HR and HRV to ensure that the body has an optimal condition for blood flow. ANS can be divided into the sympathetic and the parasympathetic nervous system. The sympathetic nervous system is activated during fight-or-flight situations such as physical activity or mentally demanding task. The parasympathetic nervous system is active during relaxation and recovery. HRV is increasing during parasympathetic activity, whereas HR is decreasing. HRV can be used to measure and analyze the state of the recovery. HRV can be measured by detecting RRI from the ECG signal. Time variation between heartbeats is presented in Figure 4. [4, 20]

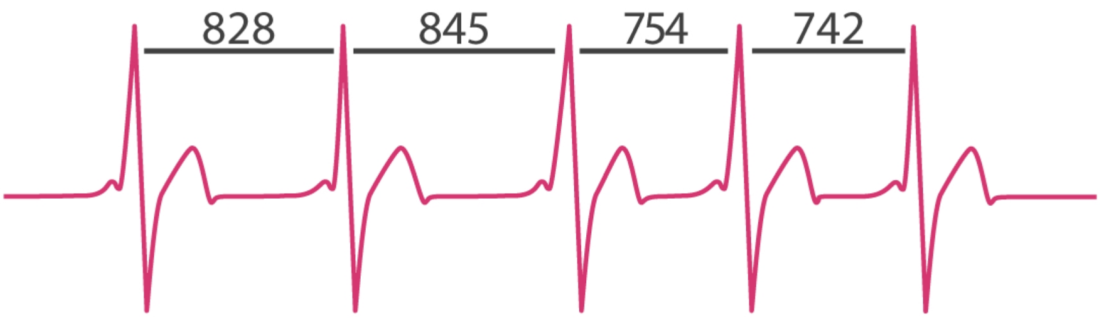

Figure 4. HRV is measured by detecting RRI from the ECG signal, the time between R peaks are in milliseconds. [21]

Physiological monitoring is used to prevent undesired conditions. Overtraining (OT) is a severe long-term condition where athletic performance is reduced. Prevention of the OT is important for athletes to keep their performance optimal. Monitoring the TL and the recovery of the athlete can be used to prevent OT. HRV is usually low for individuals with OT condition. Overreaching (OR) is a physiological state where physical performance is reduced due to the high TL and intensity of the exercise. OR is a short-term condition, which is often part of the athletes' training program. Enough recovery is needed after OR to improve the performance of the athletes. [20]

Oxygen consumption (VO_2) is one of the most reliable ways to measure aerobic activity. VO_2 can be estimated using HR and RRI measurements. The respiration rate is closely related to HR, and therefore respiration rate can improve the accuracy of the VO_2 estimation. [22] Excess post-exercise oxygen consumption (EPOC) can be estimated indirectly from HR. During EPOC body's metabolic rate is increased that leads to the increased HR and respiration rate. In other words, oxygen consumption increases after exercise. Level of the EPOC is increased due to the higher intensity or longer length of the exercise. [23]

2.3 Wireless communication today

Wireless communication technologies are emerging fast and there are various protocols for different use cases. In this chapter, we compare the properties of the different wireless communication protocols that have a potential for real-time monitoring applications.

ZigBee is a low-power wireless communication technology that is typically used to make wireless mesh networks. ZigBee uses same 2.4 GHz unlicensed industrial, scientific and medical frequency band (ISM) as Bluetooth protocols. The range for data transmission is between 10 to 100 meters, however, the ZigBee offers lower data rate compared with the other wireless communication protocols. [2]

BlueRobin is wireless communication protocol developed by BM innovations. BlueRobin uses 868 MHz and 915 MHz frequency bands with a range up to 800 meters. The protocol is designed especially for sports and healthcare applications with low-power consumption. BlueRobin is optimized for low-power and long-range, and therefore the maximal data rate is only 512 bits per second. [24, 25]

ANT+ is a protocol for monitoring sensor data. Garmin owns ANT+ protocol and it is mostly used for HR sensors to connect with sports watches and smartphones. ANT+ is using 2.4 GHz (ISM) frequency band. ANT+ specifications have many similarities with BLE, however, ANT+ is more concentrated on sensor network applications. Mesh networks are also supported by the ANT+ protocol. [26, 27]

Wi-Fi is one of the most well-known wireless communication protocols used mainly for wireless local area networks (WLAN) to provide internet access. Wi-Fi use 2.4 and 5 GHz frequency bands. Wi-Fi has a high data rate, but also higher power consumption compared with other wireless communication protocols. A Typical Wi-Fi transmitter has a range up to 100 meters. [28, 29]

Bluetooth 5 is the latest Bluetooth Special Interest Group (SIG) standard. Bluetooth 5 standard has similarities with BLE, but it has higher range and data rate. Bluetooth 5 has a range up to 400 meters with maximum data rate 2 Mbit/s, the longest range can be used only with the lower data rate. Bluetooth 5 use 2.4 GHz (ISM) frequency band. Bluetooth 5 has new features for continuous data transmission, for instance, it has the ability to chain advertising packets. [30, 31]

Bluetooth Low Energy (BLE) protocol has a high market adoption rate and reasonable range. BLE can be used for various application and most wireless devices today have BLE compatibility. Table 1 presents the comparison between different wireless communication protocols. BLE is sufficient for all-around use and it does not have any significant weaknesses. According to a study where the power consumption was compared with BLE, ZigBee, and ANT sensor nodes, BLE had the lowest power consumption among those three protocols [32].

Table 1. Comparison between different wireless communication protocols. [2, 25, 29, 31]

	BLE	**Bluetooth 5**	**ANT+**	**Wi-Fi**	**BlueRobin**	**ZigBee**
Power consumption	Very Low	Very Low	Low	High	Very Low	Low
Max range	100 m	400 m	30 m	100 m	800 m	100 m
Frequency band	2.4 GHz	2.4 GHz	2.4 GHz	2.4 and 5 GHz	868 and 915 MHz	2.4 GHz
Market adoption	Very High	High	High	Very High	Low	High (industrial use)
Max data rate	1 Mbps	2 Mbps	60 Kbps	1.73 Gbps	512 bps	250 Kbps

We selected BLE to be used in this real-time monitoring system because it is supported by many devices on the market and has adequate properties for real-time monitoring use.

Bluetooth 5 has promising features, however, there are not many sensor systems that support Bluetooth 5 today.

2.4 Bluetooth Low Energy

Bluetooth (BT) is a wireless technology standard developed for short-range communication. BT was created by Ericsson in 1994. In 1998 Bluetooth Special Interest Group (SIG) was founded by Ericsson, Nokia, Toshiba, Intel, and IBM. Today over 33000 companies have Bluetooth SIG membership [33]. BT is operating in 2.4 GHz (ISM) frequency band. ISM stands for an unlicensed industrial, scientific and medical frequency band [34].

Bluetooth Low Energy (BLE) is the BT protocol used for low-power applications. BLE 4.0 was introduced in 2010 and today it is one of the most used wireless communication protocols due to the high growth of the smartphone market. Originally, BLE was developed by Nokia as Wibree before Bluetooth Special Interest Group adopted it. BLE was designed with a principle to make power consumption as low as possible. [35]

For data transmission, BLE uses Adaptive Frequency Hopping (AFH) that enables 1600 hops per second [34]. BLE has a relatively long range for low-power wireless communication, and there are unofficial range tests where BLE connection could receive data up to 350 meters away [30]. Some BLE module manufacturers claim that their device has the range up to 500 meters.

BLE has two data transmission modes, an advertising mode, and a connected mode. The advertising mode's primary task is to send advertising packets that central device can discover available peripheral devices and send connection requests. The connected mode enables D2D communication between the peripheral and the central device. Before establishing the D2D communication peripheral device needs to use the advertising mode to be discovered by the central device. However, the advertising mode can be used for data transmission alone by sending continuously updating real-time data.

BLE protocol is divided into different layers, see Figure 5. Generic Access Protocol (GAP) is the highest a BLE protocol layer, which can directly communicate with the application layer. GAP defines roles for the D2D communication, the broadcaster role can only send advertising packets and the observer role is able to receive advertising packets.

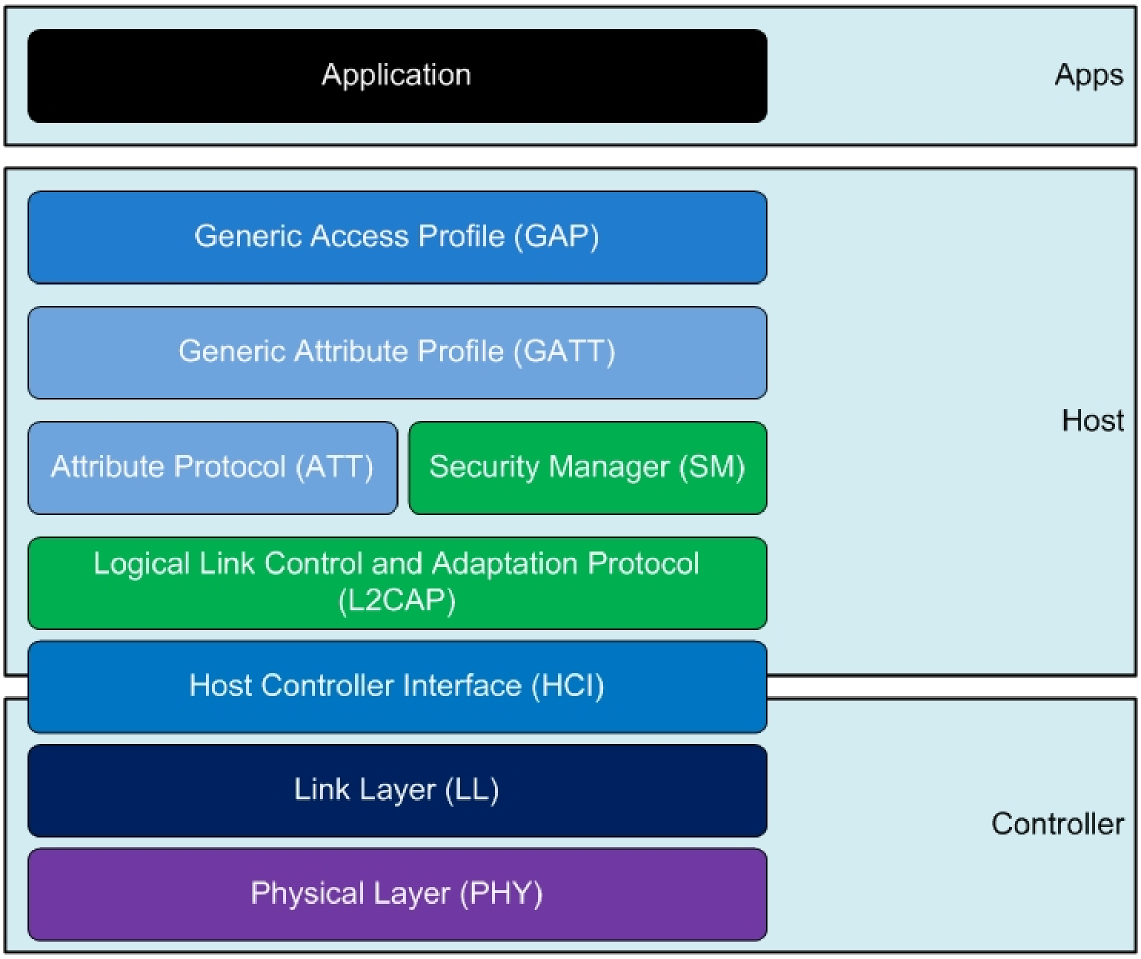

Figure 5. BLE protocol stack. [36]

The peripheral role can send information to other devices to create a connection link. The central role can send a connection request for establishing the link between BLE devices. Multiple GAP roles can be used at the same time in BLE protocol stack. [36, 37]

Generic Attribute Profile (GATT) is the second highest BLE protocol layer built on Attribute Protocol (ATT). GATT include Services and Characteristics. Battery Service is an example of a typical BLE service, that uses the battery level as a characteristic. [38]

2.4.1 Advertising mode

BLE advertising mode enables discovery of the peripheral devices to the central device. Advertising mode can be used for obtaining real-time information from the sensor devices to the mobile device.

BLE radio has 40 channels (0 to 39) in total where channels 37, 38 and 39 are the advertising channels. The rest of the channels are for data transmission. Each BLE channel has 2 MHz spacing. Advertising packets in BLE are 37 bytes long. The header is 6 bytes and the maximum payload is 31 bytes. The header and payload ratio of advertising packets are presented in Figure 6.

Figure 6. Use of advertising channels in BLE. [30]

In the BLE protocol all the advertising packets have the same payload structure, and therefore it is not possible to change the size of the packet during the advertising event. Same advertising data is usually transmitted three times once on each advertising channel (37, 38 and 39) this improves the probability of receiving the sent advertising packet. [30]

BLE has four different types of Protocol data units (PDU) for advertising. These four different advertising types are the connectable undirected advertisement (ADV_IND), the connectable directed advertisement (ADV_DIRECT_IND), the scannable undirected advertisement (ADV_SCAN_IND), the non-connectable undirected advertisement (ADV_NON_CONN_IND). Table 2 presents different features of advertising types. [36]

Table 2. BLE Advertising PDUs. [36]

Advertising PDU	Description	Max advertising data length	Max scan response length	Allow connect
ADV_IND	Used to send connectable undirected advertisement	31 bytes	31 bytes	Yes
ADV_DIRECT_IND	Used to send connectable directed advertisement	N/A	N/A	Yes
ADV_SCAN_IND	Used to send scannable undirected advertisement	31 bytes	31 bytes	No
ADV_NON-CONN_IND	Used to send non-connectable undirected advertisement	31 bytes	N/A	No

The advertising intervals for connectable undirected advertisement (ADV_IND) range from 20 milliseconds to 10.24 seconds. The advertising interval can be adjusted according to the needs of the application. However, fast advertising interval will increase the power consumption of the device significantly. Advertising packets are sent in periodic intervals, but there are random delays between zero to ten milliseconds added to the advertising interval. These random delays are to prevent collisions between advertising packets from different devices. Figure 7 presents how the advertising interval is formed on three different channels. [36, 39]

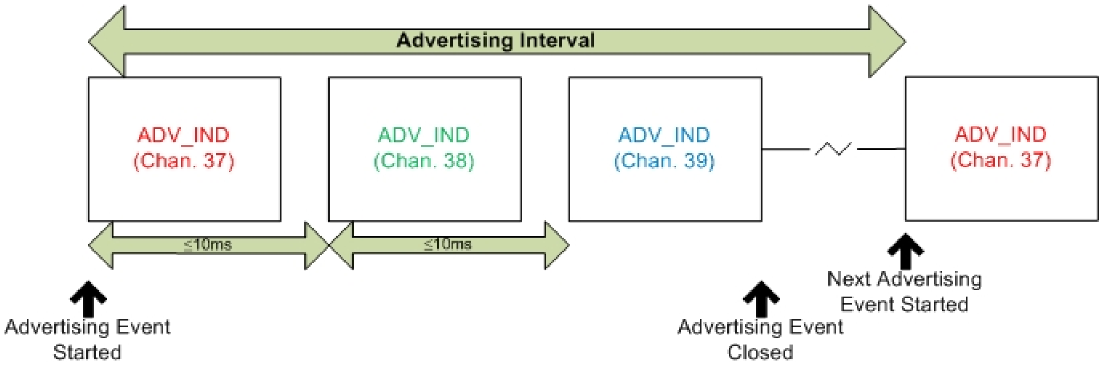

Figure 7. BLE advertising interval. [36]

BLE device can scan or advertise when it does not have a connection with another device. The scanner is either active or passive. The active scanner can receive advertising packets and request for scan response (SCAN_RSP) data from the advertiser by sending scan request packet (SCAN_REQ). The passive scanner only receives advertising packets. In passive scanning, the advertiser does not get any information if the packet is received or not, and therefore peripherals cannot detect the passive scanner. The passive scanner can be used in an application where communication with the advertiser is not needed, such as packet sniffer. Scan interval range is adjustable between 20 milliseconds to 10.24 seconds. Scan duration can be from ten milliseconds to infinity. Active and passive scanners are presented in Figure 8. [36]

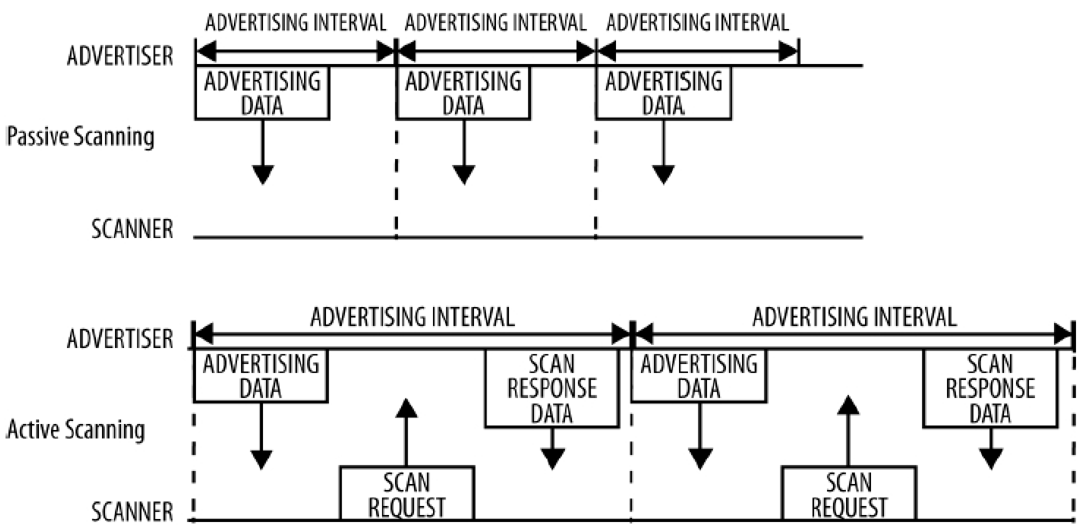

Figure 8. Active and passive scanner. [40]

2.4.2 Connection

To make a connection link between two BLE devices the peripheral and the central GAP roles are used. The peripheral role (slave) is commonly used to create a single connection with the master device. The central role (master) can make a connection requests (CONNECT_REQ) with multiple slave devices. The peripheral role device uses the advertising mode to be seen visible for the central role device. [41]

In most use cases, the mobile device is a master and the sensor device is a slave. After establishing the connection event between master and slave, they can start communicating. The master device will start the connection event by sending a CONNECT_REQ packet to the slave. During a connection event, all the communication is done through the same frequency channel. The connection interval is time between two connection events including fixed delays. Lengths of the connection events are dynamic depending on how much data the slave can send. However, the connection event must fit inside the connection interval, and therefore the connection interval limits the length of the connection event. The connection interval has range from a minimum 7.5 milliseconds to a maximum of 4 seconds. [8, 42, 43]

The number of simultaneous BLE connections between central and peripheral devices depends on the hardware of the device. For instance, Apple's computers can create a maximum of 7 connections with BLE devices [44].

2.5 EEPROM memory

EEPROM memory is used for storing the data during real-time monitoring to ensure that all the data is saved. EEPROM chip was selected for this sensor device due to its low power consumption and robustness.

EEPROM (Electrically erasable read-only memory) is a non-volatile memory based on floating gate transistors. EEPROM is an enhanced version of EPROM (Erasable programmable read-only memory) which is not electrically erasable. EEPROMs are mostly used to store a small amount of data in embedded microcontrollers, computers and other electronic devices. Non-volatile memory can store data for years without permanent power supply. In comparison to more advanced flash memories, EEPROM has relatively low writing speed. EEPROM can write or erase a single byte, which can be useful in embedded systems with low computing power.

EEPROM’s functionality is based on the floating gate MOS transistor. The floating gate transistor was presented by Frohman-Bentchkowsky in 1971. The floating gate transistor applies Nordheim tunneling and hot-carrier injection to trap electrons. [45]

EEPROM has a longer write time in comparison with the Flash memory. However, read time in EEPROM is similar with the Flash memory. The typical cell size of EEPROM is slightly bigger than other Non-volatile memory types have, and therefore EEPROMs are usually used to store a small amount of data. The lifetime of the EEPROM is usually 100

000 write cycles or more. In Table 3 we have the comparison of the different memory types.

Table 3. Memory types and their features. [46]

	Type of memory	Number of possible write/erase cycles	Write time per memory cell	Typical cell size with 0.8-µm technology
RAM	Volatile	unlimited	70 ns	1700 µm^2
Flash	Non-volatile	10 000–100 000	10 µs	200 µm^2
EEPROM	Non-volatile	100 000–1 000 000	3–10ms	400 µm^2
EPROM	Non-volatile	1	50 ms	200 µm^2
FRAM	Non-volatile	10^{10}–10^{14}	100 ns	200 µm^2
PROM	Non-volatile	1	100 ms	-
ROM	Non-volatile	0	-	100 µm^2

3. MATERIALS AND METHODS

The system evaluated for real-time monitoring of team sports consists of sensor devices and a mobile device. Devices were selected according to criteria for real-time monitoring of multiple athletes at the same time. Both sensor and mobile device must have BLE compatibility for communication and hardware that is durable to be used in professional sports. The system should enable possibilities for further development, and therefore programmability of the sensor and mobile device is an important feature.

In this project, the advertising mode is used to send real-time HR data from up to 30 athletes simultaneously. The advertising mode was not originally made for real-time data transmission; however, the contents of the advertising packets and the advertising intervals can be changed conveniently. Normally, the central device can make a limited number of the connections, and therefore it is not possible to monitor a large number of the connected sensor devices simultaneously. Nonetheless, the central devices can scan many of the advertising packets from multiple peripheral devices. Ability to scan a large number of the advertising packets is utilized for this real-time monitoring system.

However, wireless communication is not always reliable, and a mobile device might miss some advertising packets. Therefore, the sensor device must have internal memory that can record all the HR data. The role of the mobile device would be HR data acquisition and establishing connections with the sensor devices.

3.1 Sensor device

Sensor device used for this real-time monitoring system is called Movesense and it is manufactured by Suunto. The Movesense device has an open source development platform which enables third parties to create their own applications and features for the sensor device. Movesense uses Representational State Transfer (REST) application programming interface (API) that is based on the Hypertext Transfer Protocol (HTTP) commands. REST-type architecture communicates between different sensors inside the Movesense device. The Movesense device is shown in Figure 9. [47, 48]

Figure 9. Movesense device is used to monitor heart rate and broadcast data in real-time using advertising mode.

Movesense supports BLE and enables the use of the advertising mode and the connected mode. Both BLE modes are needed for our real-time monitoring system.

Movesense has a compact size and it is powered by a replaceable CR 2025 lithium-ion battery. Along with the HR sensor the Movesense is equipped with 9-axis motion sensor with accelerometer, gyroscope, and magnetometer. Movesense also has a thermometer and red light-emitting diode (LED), which can be controlled by the software. Each sensor can be utilized using REST commands which makes testing and creating new features easier. Movesense is built with low-power electronic components and each sensor can be used separately according to needs of the application. The list of different components is presented in Table 4. [49]

Table 4. List of the components integrated into the Movesense. [49, 50, 51, 52, 53]

	Product name	Supplier
Energy source	CR 2025 Li-Ion battery	-
MCU	nRF52832	Nordic Semiconductor
Accelerometer and gyro-scope combo	LSM6DSL	STMicroelectronics
Magnetometer	LIS3MDL	STMicroelectronics
Temperature sensor	TMP112	Texas Instruments
Heart rate sensor	MAX30003 Biopotential Analog Front-End	Maxim Integrated

Movesense is designed to be small and robust sensor device and it weighs only 10 grams. The sensor is shock and water resistant up to 30 meters, and it can be used for swimming and other demanding conditions.

3.1.1 Microcontroller unit and radio

The radio for BLE communication is an important part of the Movesense device. During the real-time monitoring, BLE radio is used to broadcast advertising packets, and therefore it should be configurable for our application.

The Movesense uses nRF52832 microcontroller unit (MCU) from Nordic Semiconductors. The nRF52832 is an advanced low-power system on chip (SoC) including a radio for BLE communication. Multiprotocol radio has hardware support for Bluetooth 5 and is compatible with ANT protocol. The Movesense is built to support BLE with present hardware setup. [54]

The nRF52832 SoC is designed for low-power applications and it can be used with a supply voltage from 1.7 to 3.6 volts. The central processing unit (CPU) of the nRF52832 use 32-bit ARM Cortex-M4F equipped with 512kB flash memory and 64kB RAM memory. [55, 56]

3.2 Scanner device

iPad Air 2 was used for evaluating this real-time monitoring system. Apple's iPad Air 2 was used for evaluation since Apple products have usually uniform hardware and operating system (OS) between their devices. iPad Air 2 has support for BLE 4.2 and therefore it is compatible with Movesense devices [57]. Devices powered by Android OS could be used for this real-time monitoring system, but there are plenty of Android devices with different hardware and OS and that makes evaluation more complex. iPad Air 2 is presented in Figure 10.

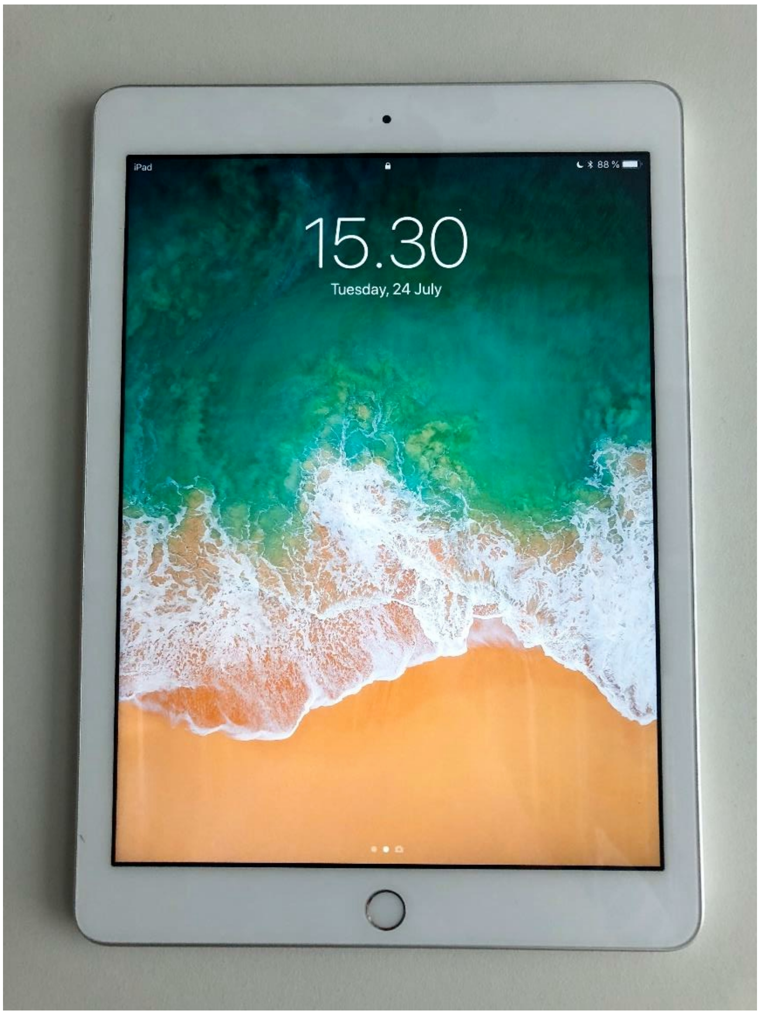

Figure 10. iPad Air 2 was used for scanning advertising packets sent by the Movesense device.

iPad Air 2 has a role of the central device in this system. iPad scans advertisement packets broadcasted by multiple Movesense devices. iPad is used to create a secure connection between Movesense when we need to download internal memory or change settings for the Movesense device.

Other BLE devices were tested before selecting iPad for the evaluation, such as Cassia C1000 Bluetooth router. Cassia is an external Bluetooth hub that can connect with computers or smartphones via ethernet. Cassia hub worked well as a scanner for BLE advertisement packets; however, Cassia needs an external power source and the device has a large size which is not good for mobile use. Benefits of the external hub were not much better compared to iPad, and therefore evaluation was continued using iPad as a scanner and central device for the BLE communication. Cassia C1000 Bluetooth router is presented in Figure 11. [58]

Figure 11. Cassia C1000 Bluetooth router.

3.3 Test protocols

For evaluation, multiple tests were made to find the right settings for the device. Firstly, we tested different settings for BLE advertising mode. An iPad was used for scanning advertising data and creating a connection with the Movesense device. The testing environment at the office had various other BLE devices, and therefore it was a good environment to see how well BLE is working when there are many interferences. Also, nRF Sniffer made by Nordic Semiconductor was used for monitoring BLE traffic. Sniffer is useful for debugging and monitoring BLE advertising packets while testing the device. However, nRF Sniffer cannot scan BLE advertising packets from long distances, consequently, we only used it for short-range monitoring [59].

3.3.1 Field test protocols

Field tests were made in real-life conditions to demonstrate how well the real-time monitoring system is working. Before the field tests with real athletes, we made shorter tests in the office environment. To figure out the optimal BLE advertising interval several different advertising intervals were tested. A faster advertising interval also increases power consumption, and therefore the trade-off between power consumption and lost advertising packets should be considered. The advertising interval of 211.25 milliseconds was selected for field tests and it was also one of the advertising intervals recommended by Apple [60]. This advertising interval was changed to Movesense devices only. Even though the advertising interval was set for the 211.25 milliseconds the advertising payload was updated once a second, which means that the same advertising data was sent multiple times. The lost advertising packet ratio is calculated for the updated payload data only, and therefore we cannot know the actual amount of the lost advertising packets.

Field tests were done with 10 to 20 devices broadcasting BLE advertising data simultaneously. In these tests, advertising data included a simulated heart rate and only the lost advertising packet ratio was evaluated. Simulated heart rate changed every second sequentially between 60 and 200 beats per minute (BPM). The pilot field test was done at the ice hockey rink located in Tampere, Finland. In this test 10 Movesense sensors were monitored at the same time. However, due to lack of the test subjects three players wore three sensor each and one sensor was left opposite of the ice hockey rink. Players wore sensors under ice hockey gears using chest straps. We were using iPad as a scanner at the team bench next to ice hockey rink. All the ice hockey players used in this test were nonprofessionals. The ice hockey rink is located at the underground facility with rock walls, which might give stronger BLE signal because of reflections from the walls. The ice hockey rink has a length of 61 meters and width of 30 meters. In total this test took 48 minutes. In Figure 12 the location of the iPad at the ice hockey rink is presented.

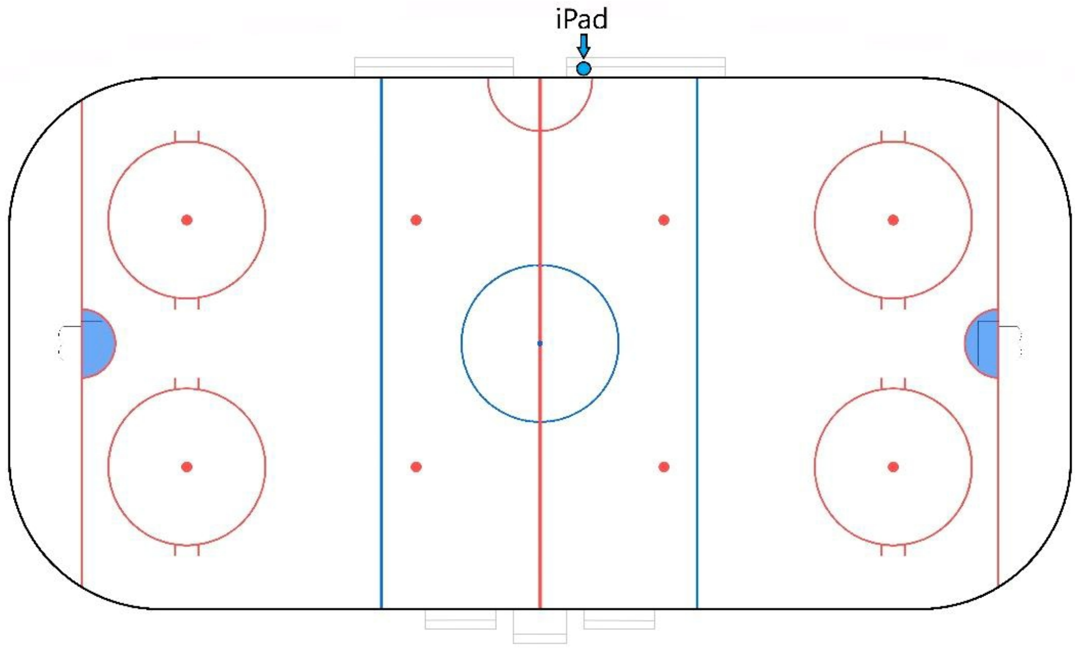

Figure 12. Ice hockey rink and the location of the iPad. [61]

The second field test was held at an indoor football hall located in Jyväskylä, Finland. For this test 20 test subjects were used. As test subjects, we had 19 football players and one coach. In this test, Movesense device used the same settings and configurations as in the pilot field test, which was held at the ice hockey rink. Distances between receiver and sensors were larger in this test, and thus we can see how the system is working with the more demanding environment. The football pitch has a length of 105 meters and is 65 meters wide. The longest possible distance between the iPad and the Movesense device was approximately 85 meters. iPad was used as a receiver near the sideline of the football field. In Figure 13 the location of the iPad at the football pitch is presented.

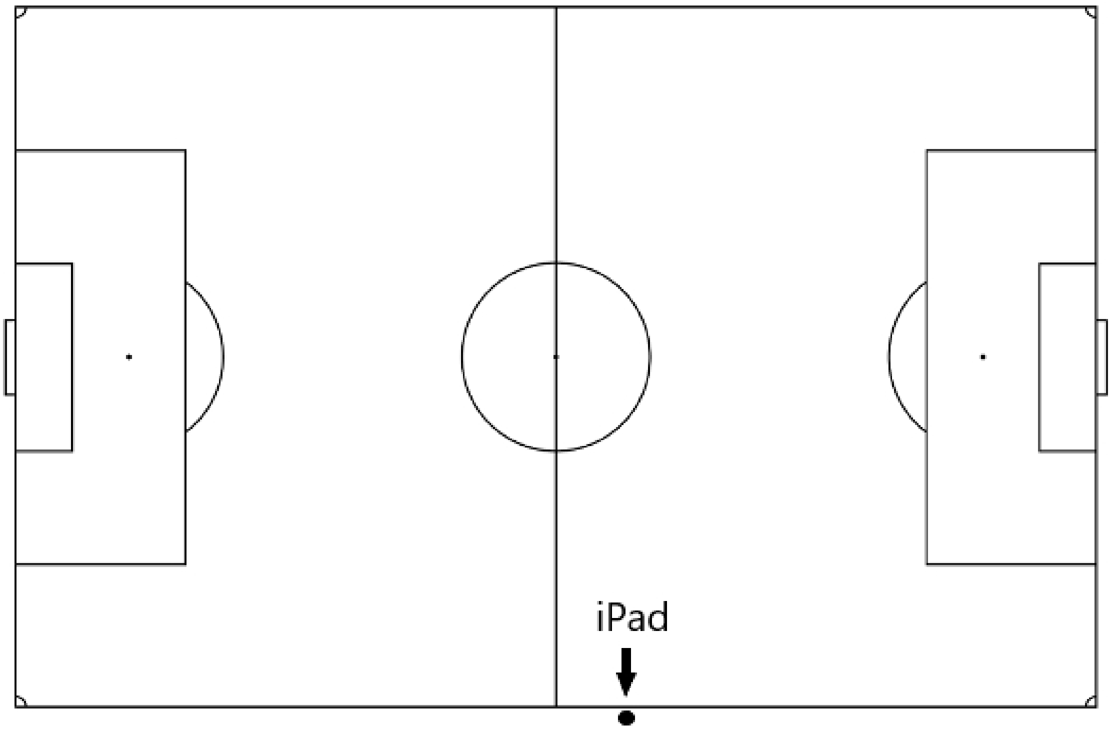

Figure 13. Football pitch and location of the iPad. [62]

During the test, distances between players varied a lot which led to a higher deviation of the lost BLE advertising data among the test subjects. This test took 1 hour and 30 minutes.

3.3.2 Range test protocol

One of the objectives of this thesis was to evaluate the range of the real-time monitoring system. Range test was executed at the football pitch with the length of 100 meters. Test location was outdoor and there were not many other interferences, such as BLE traffic or other wireless connections. For the Movesense devices, BLE advertising interval of 211.25 milliseconds was used during the range test.

During the range test, two Movesense devices were worn on the chest strap by the test subject. The iPad was still in the same place during the range test. Test subject walked away from the iPad and stopped every 10 meters for one minute until 100 meters were reached. Whenever test subject halted for one minute, the test subject also turned facing towards to the iPad. A total length of the range test was 20 minutes.

3.3.3 Internal memory test protocol

Along with the BLE advertising, the internal memory is important for the overall functioning of the real-time monitoring system. Therefore, reading the EEPROM of the Movesense device should work well in all situations.

Download times of the internal memory were tested using the iPad. When creating BLE connection between iPad and the Movesense we can make REST commands to read EEPROM memory. Four measurements with different length were used to define the reading time of the internal memory. Time used for creating BLE connection was not measured, but it should be considered when estimating the total time used for downloading the internal memory.

3.4 Statistical analysis

The test results were statistically analyzed using descriptive statistics. Shapiro-Wilk test was used to see if the field test results are normally distributed. After the results of the field tests were confirmed to be normally distributed, t-test was used to see if the test results are significantly different. By determining that the difference is real between test cases we can make conclusions that different distances and testing environments will have a real impact on the packet loss ratio of the advertising data. Without verifying if there is a statistically significant difference between tests, we cannot be sure if the difference is arbitrary or genuine. However, this kind of statistical analysis does not tell if the results are good or not, but we can see how the test cases differ between each other and if the difference is significant.

T-tests are statistical tests that can be used to compare differences between the means of the two data groups. T-tests can be performed as an independent test or a paired test. To do t-tests the data groups used for comparison should be normally distributed, which can be tested with Shapiro-Wilk test. We used Welch two-sample t-test for our statistical analysis. The Welch two-sample t-test is an independent test. Welch two-sample t-test is a variant of Student's t-test, thus it is created for data groups with different variances and sample sizes. The null hypothesis for Welch two-sample t-test in our statistical analysis is that two data groups have equal means. Welch two-sample t-test is presented in Equation 1. [63, 64]

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \tag{1}$$

In the equation $\bar{X}_1$ stands for mean, s_1^2 is the sample variance and N_1 is the sample size for the 1st data group. Whereas for the 2nd data group $\bar{X}_2$ stands for mean, s_2^2 is the sample variance and N_2 is the sample size. [64]

Shapiro-Wilk test was published by statistician Samuel Sanford Shapiro and Martin Wilk in 1965. Originally this test was made to analyze sample sizes smaller than 50. Shapiro-Wilk test is a powerful test that can be used to analyze random ordered samples effectively, and therefore it has become one of the most used methods for testing normal distribution. The null hypothesis for Shapiro-Wilk test is that distribution is normal. Shapiro-Wilk test is presented in Equation 2.

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n} (x_i - \overline{x})^2} \tag{2}$$

In the equation $x_{(i)}$ is i^{th} order of statistic, which refers to the i^{th} smallest number in the sample. $\overline{x}$ is the sample mean $\overline{x} = (x_1 + .. + x_n)/n$

The constants a_i are derived from $a_i = (a_i, \dots, a_n) = \frac{m^T V^{-1}}{(m^T V^{-1} V^{-1} m)^{1/2}}$ where $m = (m_1, \dots, m_n)^T$ represent an order of the values that are expected. V is the covariance of the order statistics. W is the value that gives the result of the normal distribution. W values vary between zero and one. Value of W_α indicates the critical value for a specific significance level and the sample size. If the test statistic value W is less than the critical value W_α we can reject the null hypothesis that distribution is normal. We will also calculate the p-value to determine if the W values are probable according to the selected significance level. Critical values for different sample sizes and significance levels are presented in Table 5. [65, 66]

Table 5. Shapiro-Wilk test critical values for different sample sizes and significance levels. [66]

n	$W_{0.01}$	$W_{0.02}$	$W_{0.05}$	$W_{0.10}$	$W_{0.50}$
3	0.753	0.756	0.767	0.789	0.959
4	0.687	0.707	0.748	0.792	0.935
5	0.686	0.715	0.762	0.806	0.927
6	0.713	0.743	0.788	0.826	0.927
7	0.730	0.760	0.803	0.838	0.928
8	0.749	0.778	0.818	0.851	0.932
9	0.764	0.791	0.829	0.859	0.935
10	0.781	0.806	0.842	0.869	0.938
11	0.792	0.817	0.850	0.876	0.940
12	0.805	0.828	0.859	0.883	0.943
13	0.814	0.837	0.866	0.889	0.945
14	0.825	0.846	0.874	0.895	0.947
15	0.835	0.855	0.881	0.901	0.950
16	0.844	0.863	0.887	0.906	0.952
17	0.851	0.869	0.892	0.910	0.954
18	0.858	0.874	0.897	0.914	0.956
19	0.863	0.879	0.901	0.917	0.957
20	0.868	0.884	0.905	0.920	0.959
21	0.873	0.888	0.908	0.923	0.960
22	0.878	0.892	0.911	0.926	0.961
23	0.881	0.895	0.914	0.928	0.962
24	0.884	0.898	0.916	0.930	0.963
25	0.886	0.901	0.918	0.931	0.964
26	0.891	0.904	0.920	0.933	0.965
27	0.894	0.906	0.923	0.935	0.965
28	0.896	0.908	0.924	0.936	0.966
29	0.898	0.910	0.926	0.937	0.966
30	0.900	0.912	0.927	0.939	0.967
31	0.902	0.914	0.929	0.940	0.967
32	0.904	0.915	0.930	0.941	0.968
33	0.906	0.917	0.931	0.942	0.968
34	0.908	0.919	0.933	0.943	0.969
35	0.910	0.920	0.934	0.944	0.969
36	0.912	0.922	0.935	0.945	0.970
37	0.914	0.924	0.936	0.946	0.970
38	0.916	0.925	0.938	0.947	0.971
39	0.917	0.927	0.939	0.948	0.971
40	0.919	0.928	0.940	0.949	0.972
41	0.920	0.929	0.941	0.950	0.972
42	0.922	0.930	0.942	0.951	0.972
43	0.923	0.932	0.943	0.951	0.973
44	0.924	0.933	0.944	0.952	0.973
45	0.926	0.934	0.945	0.953	0.973
46	0.927	0.935	0.945	0.953	0.974
47	0.928	0.936	0.946	0.954	0.974
48	0.929	0.937	0.947	0.954	0.974
49	0.929	0.937	0.947	0.955	0.974
50	0.930	0.938	0.947	0.955	0.974

Standard deviation (SD) tells us how the data samples are located around the mean of the population. Therefore, low SD means that samples are close to mean of the population, and thus high SD has a large dispersion from the mean population. We used SD to represent variation between the lost packet ratio of the BLE advertising packets from the test measurements. When the data is normally distributed 68 percent of the data is between the mean of the data and +/-SD. Two times standard deviation ($2*\sigma$) was used to include 95 percent of data between +/-SD values. The Equation 3 for the SD is defined as

$$\sigma = \sqrt{\frac{1}{\mathrm{N}} \sum_{i=1}^{n} (x_i - \mu)^2}, \tag{3}$$

where μ present the mean of all values, x_i are sample values within the data group and the N represents the size of the data group. [67]

4. MEASUREMENTS & RESULTS

4.1 Field tests

Field tests at the ice hockey rink were made at the underground facility. This was the pilot field test with real test subjects and results seemed promising. However, distances at the ice hockey rink were relatively short with the maximum distance between test subjects and the iPad being less than 40 meters. Here is the table of the statistical values from the pilot field test and the second field test. The values are calculated from the packet loss ratio of the BLE advertising packets. Table 6 presents average, +/-SD and range. We use +/-SD to present how close the data samples are within the average of the lost advertising packet ratio.

Table 6. Average lost packet ratio with standard deviation and range for the pilot field test and the second field test.

Statistical values from the field tests			
	Average	**+/-SD**	**Range (m)**
Pilot field test	0.76	0.34	40
Second field test	29.64	7.74	85

Pilot field test’s average lost packet ratio of the advertising packets was 0.76 percent which is a good ratio. It means that 99.34 percent of all advertisement data was received. However, we should keep in mind that data values were updated once a second and the advertising interval was 211.25 milliseconds, and therefore same data was sent multiple times.

The lost advertising packet ratio was measured from individual Movesense device separately, thus we can see if there are variations between different Movesense devices. In Figure 14 the packet loss ratio from the pilot field test is presented by each device. The Movesense devices are marked with device numbers so we can be sure which devices were used at the test. All the advertisement packets sent by the device number 14 were received by the iPad. The device number 14 was the only sensor which was not worn by a test subject and it was left opposite side of the ice rink. The +/-SD of the lost advertising packet ratio was 0.34 percentage and two times +/-SD was 0.68 percentage. The SD for the pilot test was high among the Movesense devices when comparing to the mean of the measurement data. The horizontal red line in Figure 14 presents the average lost advertising packet ratio.

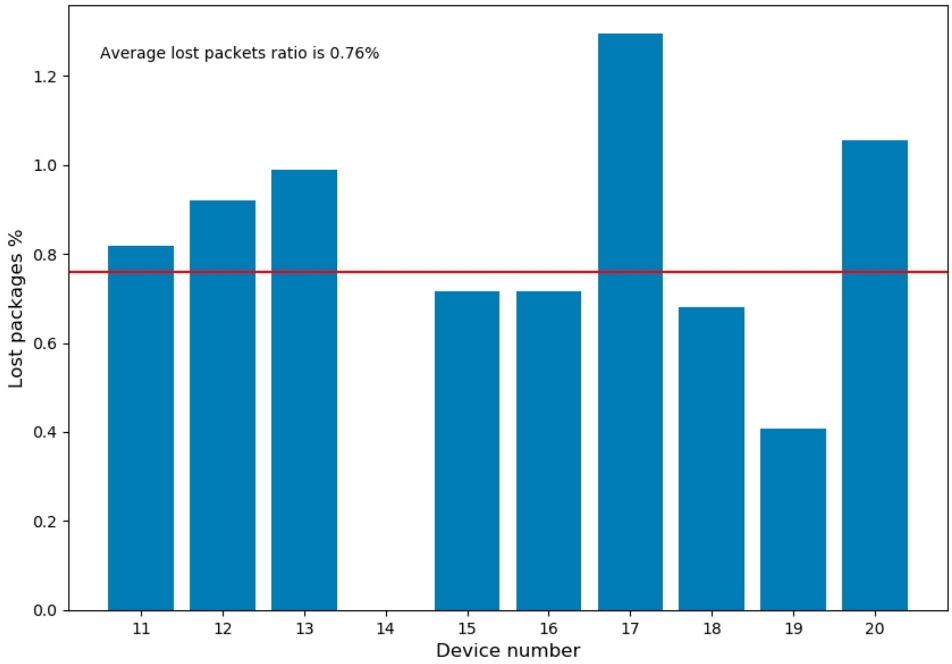

Figure 14. Lost advertising packet ratio by each Movesense device at the pilot field test.

The second field test was done at the indoor football pitch located in Jyväskylä, Finland. In comparison to the pilot field test, this test had more demanding conditions for wireless communication due to longer distances and the larger amount of the test subjects. Maximal distance between the Movesense and iPad in this test was 85 meters.

The average lost advertising ratio was almost 30 percentage which is much higher than in the pilot field test. Longer distances between the Movesense devices and the iPad was the main reason for the higher advertising packet loss ratio. However, the second field test had a lower SD compared to the pilot test, and therefore data from the devices are closer to average. Lost advertising packet ratio by each device from the second field test is shown in Figure 15.

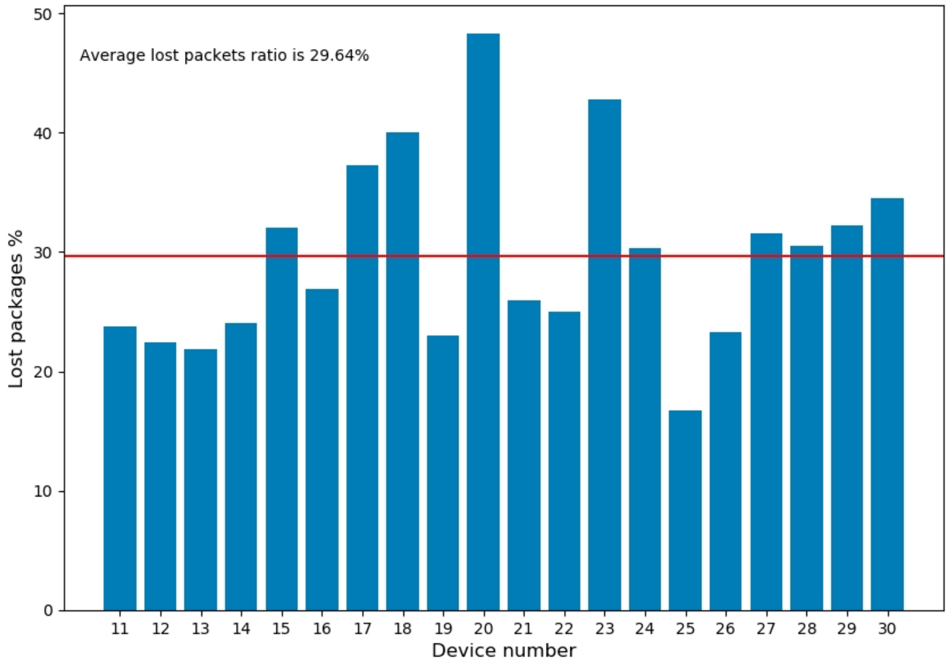

Figure 15. Lost advertising packet ratio by each Movesense device at the second field test.

When comparing RSSI levels between the pilot and second field test we can see that RSSI levels are slightly higher at the pilot field test. However, it is hard to draw the conclusion from the RSSI values alone. RSSI levels during the field tests are shown in Figure 16.

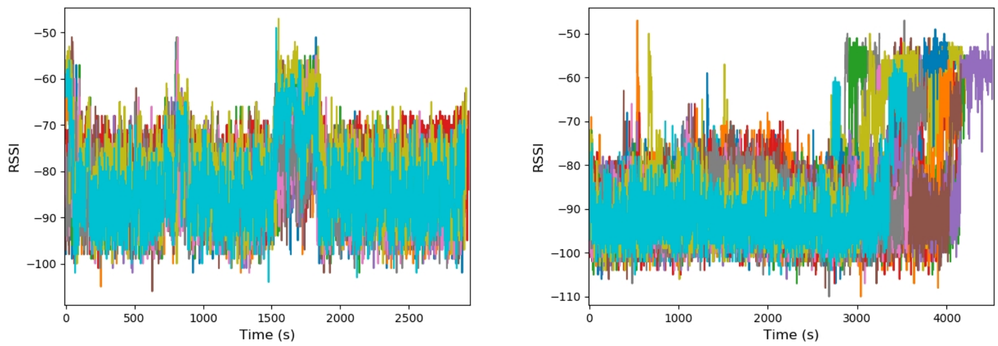

Figure 16. RSSI levels during the pilot field test (left) and the second field test (right).

To verify that the difference between the field tests is statistically significant we used Welch two-sample t-test. Before using the Welch two-sample t-test normality of the test data should be tested and for that, we used the Shapiro-Wilk test. We can assume that data is normally distributed when W value from Shapiro-Wilk test is larger than the critical value W_α. Critical value with 0.05 significance level for the pilot field test is 0.842 and for the second field test 0.905. Critical values are presented in Table 5. P-value for

Shapiro-Wilk test should be larger than 0.05 to make sure that the results are probable. Null hypothesis $\boldsymbol{H_0}$ for Shapiro-Wilk test is that the population is normally distributed. Alternative hypothesis $\boldsymbol{H_1}$ is that the population is not normally distributed. Results of the Shapiro-Wilk tests are presented in Table 7.

Table 7. Shapiro-Wilk normality test for the field test data.

Shapiro-Wilk normality test		
	W	p-value
First field test	0.94705	0.6337
Second field test	0.9459	0.3092

The results of the Shapiro-Wilk test show that W values are larger than critical values and the p-value is larger than 0.05, thus we cannot reject null hypothesis $\boldsymbol{H_0}$ and we can expect that the test data is normally distributed. The next step is to do Welch two-sample t-test for the field test data. Null hypothesis $\boldsymbol{H_0}$ means that the measurement data is not significantly different from each other which means that data groups have equal means. Null hypothesis could imply that the differences in the means between the pilot and the second field test are not significant. Alternative hypothesis $\boldsymbol{H_1}$ for the Welch two-sample t-test is that the measurement data from the field tests are significantly different from each other. The results of the Welch two-sample t-test are presented in Table 8.

Table 8. Welch two-sample t-test for the field test data.

Welch two-sample t-test						
			95 percent confidence interval		Sample estimates	
t	df	p-value	lower	upper	mean of x	mean of y
-16.23	19.156	1.187e-12	-32.60017	-25.15583	0.7595426	29.6375453

T-statistics value with 19.156 degrees of freedom is -16.23. P-value is less than 0.05 and thus we can reject the null hypothesis $\boldsymbol{H_0}$. Alternative hypothesis $\boldsymbol{H_1}$ is true, which means the data is significantly different. Upper and lower limit values for 95 percent confidence interval are -32.60017 and -25.15583. We can see that t-statistics value is out of the 95 percent confidence interval which also confirms that rejection of the null hypothesis $\boldsymbol{H_0}$ is valid. Sample estimates represent mean values of the two data groups used in the Welch two-sample test. Mean of x is 0.7595426 and it is mean of the pilot field tests lost advertising packet ratio. Mean of y is 29.6375453 referring to the mean of the lost advertising packet ratio from the second field test. Different test settings and distances have a significant impact on the lost packet ratio of advertising packets. Field testing is important for evaluating the performance of the sensor.

4.2 Range tests

Range tests were made to understand limits of the BLE advertising mode. Signal strength can be monitored by the received signal strength indicator (RSSI), which is measured by scanner device. A specific RSSI value is recorded for each advertisement packet. In this range test, we were especially interested in how different distances affect RSSI levels and the advertising packet loss ratio. Two different Movesense devices were used during the range test.

In Figure 17 comparison between RSSI levels from device number 10 and 9 are presented. Both devices had the same trend where RSSI levels are decreasing with longer distances. Gaps between every 10 meters happened because the test subject was facing backward to the iPad and the signal of the BLE is dampened by the test subject's body.

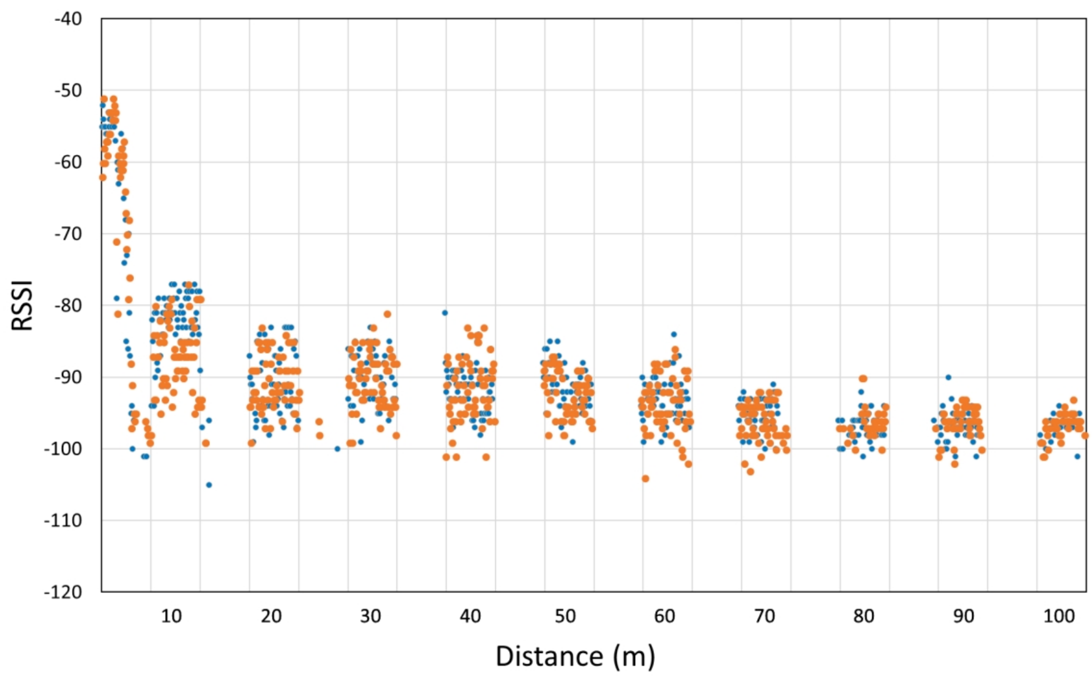

Figure 17. Comparison of RSSI levels between device number 10 (blue) and 9 (orange).

However, BLE signals are received between 0 and 10 meters while the test subject was facing backward. The test subject was only facing backward to the scanner device while walking to the next distance position. This observation is important for understanding the performance and limits of the real-time monitoring system using BLE advertising mode for data broadcasting.

Lost advertising packet ratio was calculated for each distance between 10 and 100 meters. Each advertising packet loss ratio is calculated from a one-minute measurement. However, the packet loss ratio is only calculated when the test subject is facing towards to the iPad. In Figure 18 the advertising packet loss ratio during the range test is presented.

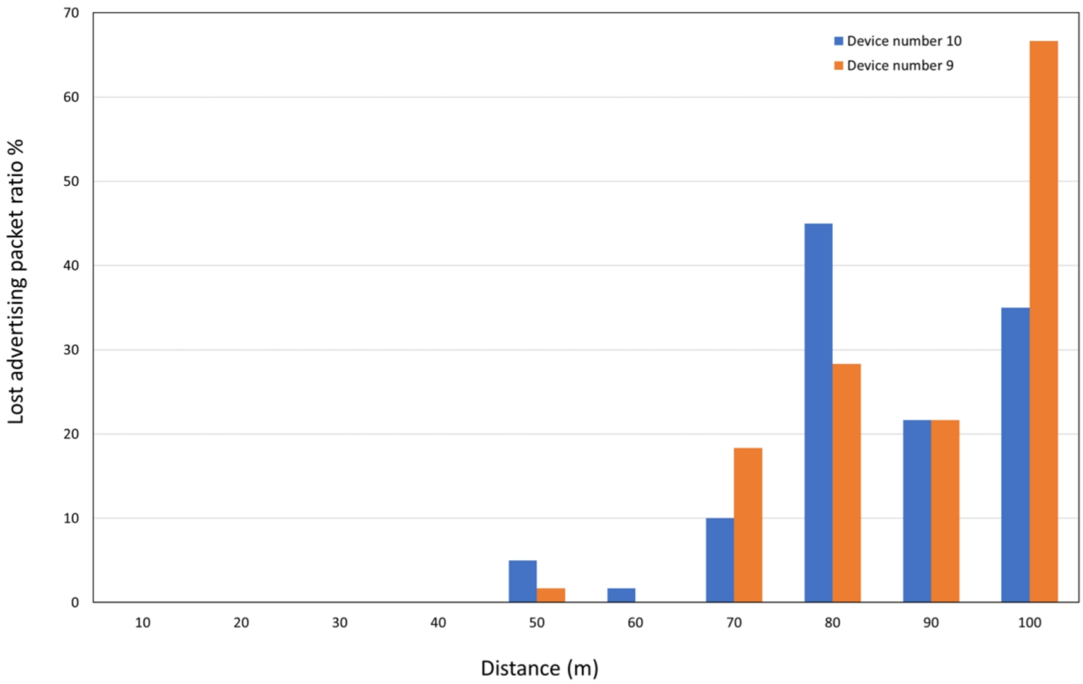

Figure 18. Lost advertising packet ratio in percentage for different distances.

The packet loss ratio was low until 70 meters when it began to increase significantly. After 70 meters there were quite big differences in packet loss ratio between the two Movesense devices.

During the range tests, we gained more experiential knowledge that test subjects' body can block the BLE signals. However, scanner device can receive advertising packets from up to 10 meters away even though the body is blocking the signal. BLE is operating in the 2.4 GHz frequency band which is easily blocked by thick walls or even the human body. Different device location on the body or increased transmitter (TX) power could help to reduce problems related to weak signal strength.

4.3 Internal memory tests

The internal memory of the Movesense device was downloaded using iPad. EEPROM memory of the Movesense can be read with the iPad when the BLE connection is established. We used an iPad to calculate the read time of the internal memory. However, creating the BLE connection between iPad and the Movesense takes 10 to 30 seconds and the time varies a lot. Reading times of the EEPROM memory are shown in Figure 19.

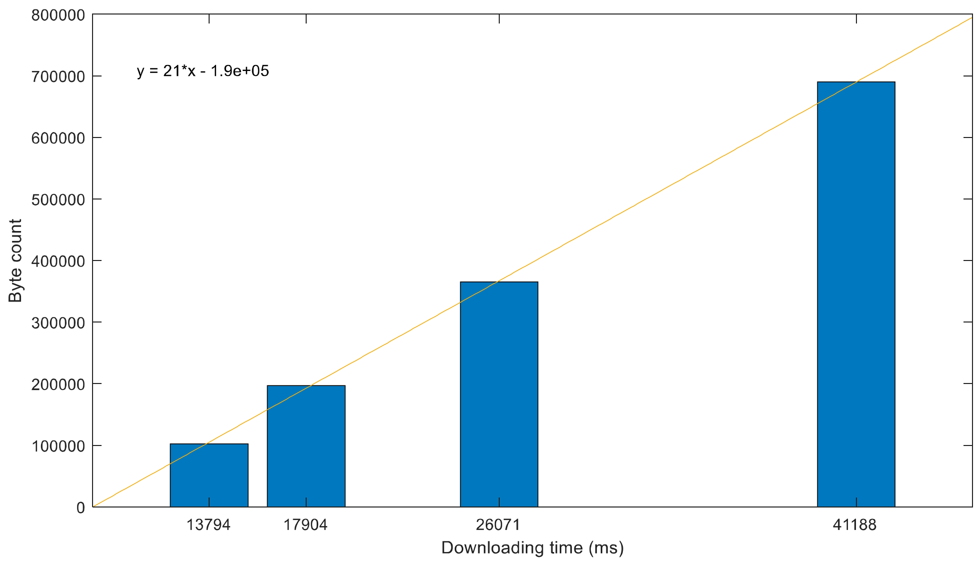

Figure 19. Reading time of the Movesense device's internal EEPROM memory.

The reading time of the EEPROM memory over BLE connection is linear and follows the line with equation $y = 21 * x - 1.9e + 05$. The linearity of the reading time means that download time will double when the byte count doubles. The linearity of the read times makes estimating download times easier.

5. DISCUSSION

In this Master's thesis, BLE technology was evaluated using the sensor device that can be utilized for real-time team sports monitoring. The sensor device used is called the Movesense manufactured by the Finnish company Suunto. The sensor device was evaluated according to the demanding requirements of the professional sports. Nowadays, many professional sports teams use different technologies to monitor and train their athletes, and thus we want to create a real-time monitoring system for their needs. During the work, literature review was concluded to study different wireless technologies in comparison with BLE technology.

The main objective of this project was to evaluate the suitability of the BLE advertising mode for real-time monitoring. The BLE advertising mode was tested using Cassia C1000 and iPad to receive BLE advertising packets. The iPad was selected for further testing and development due to its portability and operating system (OS). We used different advertising intervals to find out optimal settings for minimizing the advertising packet loss ratio while achieving the maximal range. The real-time monitoring system was also verified to handle up to 30 devices sending the advertising packets simultaneously. The advertising interval of 211.25 milliseconds was one of the advertising intervals recommended by Apple and according to tests it was sufficient for reducing advertising packet loss ratio, and therefore it was selected for the further tests [60].

The Movesense sensors were also tested in real life conditions. The pilot field test was held at the ice hockey rink located in Tampere, Finland. The results were promising from the pilot tests, and thus we arranged next field tests for a football team in Jyväskylä. These two field tests had different environments, so we could see if that has an influence on the advertising packet loss ratio. In Chapter 4 the results from field tests are presented and we can see that the pilot field test had a low advertising packet loss ratio. However, the second field test had a relatively high advertising packet loss ratio. We also used statistical methods to see if the difference is statistically significant. Welch two-sample t-test was used to calculate the statistical difference between the field tests. The results showed a true difference between the field tests and we can assume that different testing environments and the distances have a real impact on advertising packet loss ratio.

Range test was also arranged to find out the range and performance of the BLE technology. The advertising packet loss ratio is relatively low until the line-of-sight distance of 70 meters when it begins to increase significantly. Results from the range test showed that signal strength weakened when the test subject's body was blocking the signal directly between the Movesense and iPad, according to the test results advertising packets were not received anymore after the distance of 30 meters.

Even though the BLE advertising mode is sufficient for the real-time monitoring we need to ensure that we do not lose any information when BLE advertising packet is lost, thus data should be secured after each training session. Therefore, the Movesense's internal EEPROM memory was used to store RRI data. Download times of the EEPROM were tested using the iPad for downloading the data through BLE connection. Download times from EEPROM followed a linear function which enables more accurate estimation of the download times.

This project gave me a broad knowledge of wireless communication systems and physiological monitoring. During the work, I had an opportunity to use different tools and test methods for evaluation of the Movesense device. The time was limited, and therefore we could not perform as many field tests as anticipated. However, results from this thesis can be used for further development and validation of the real-time monitoring system. This thesis had practical and experimental approach during the whole project, and therefore results are valuable for this device setup only. Literature research in this thesis is succinct and work focused more on the practical evaluation of the system. There were not many previous studies related to team sports monitoring using BLE advertising mode, which makes this work unique.

For the future work, the power consumption of the Movesense device should be tested and optimized. Ideally, the device should have low power consumption without losing any features or accuracy of the measurement data. In addition, we should test how many Movesense devices can be connected to the iPad at the same time. This is important for reducing download times of the internal EEPROM memory. For further development of the real-time monitoring system, accelerometer and magnetometer included in the Movesense could be used to detect contexts of the physical activity. Protection and encryption for the BLE advertising packets should also be considered, to prevent possible man-in-the-middle attacks.

6. CONCLUSIONS

Technology evaluated in this thesis is feasible to be used for real-time monitoring of the team sports. An ideal environment for this real-time monitoring system is indoor sports halls with shorter distances, such as the pilot field test environment. BLE protocol has some limitation related to range and advertising mode, and thus the data should be recorded to the internal memory of the sensor device to prevent loss of the data during BLE advertising. The evaluation work gave us insight into the potential of the BLE technology to be used for demanding real-time monitoring applications. BLE advertising was used to transmit HR and other data related to the physiological state of the athlete, also we needed advertising mode for connection requests to create a secure connection between the device and iPad. More testing and evaluation are needed to fully understand the limits for the BLE advertising mode.

The results from the field tests show that the BLE advertising packet loss ratio is heavily affected by the distance and the testing environment. However, the BLE advertising mode is not originally intended for real-time monitoring applications, but for the discovery of the peripheral devices. Further validation and verification are needed to ensure the quality of this real-time monitoring system.

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